Searches for lepton flavor and lepton number violation in kaon decays at CERN

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for the NA48/2 and NA62 collaborations

Deep Inelastic Scattering 2011

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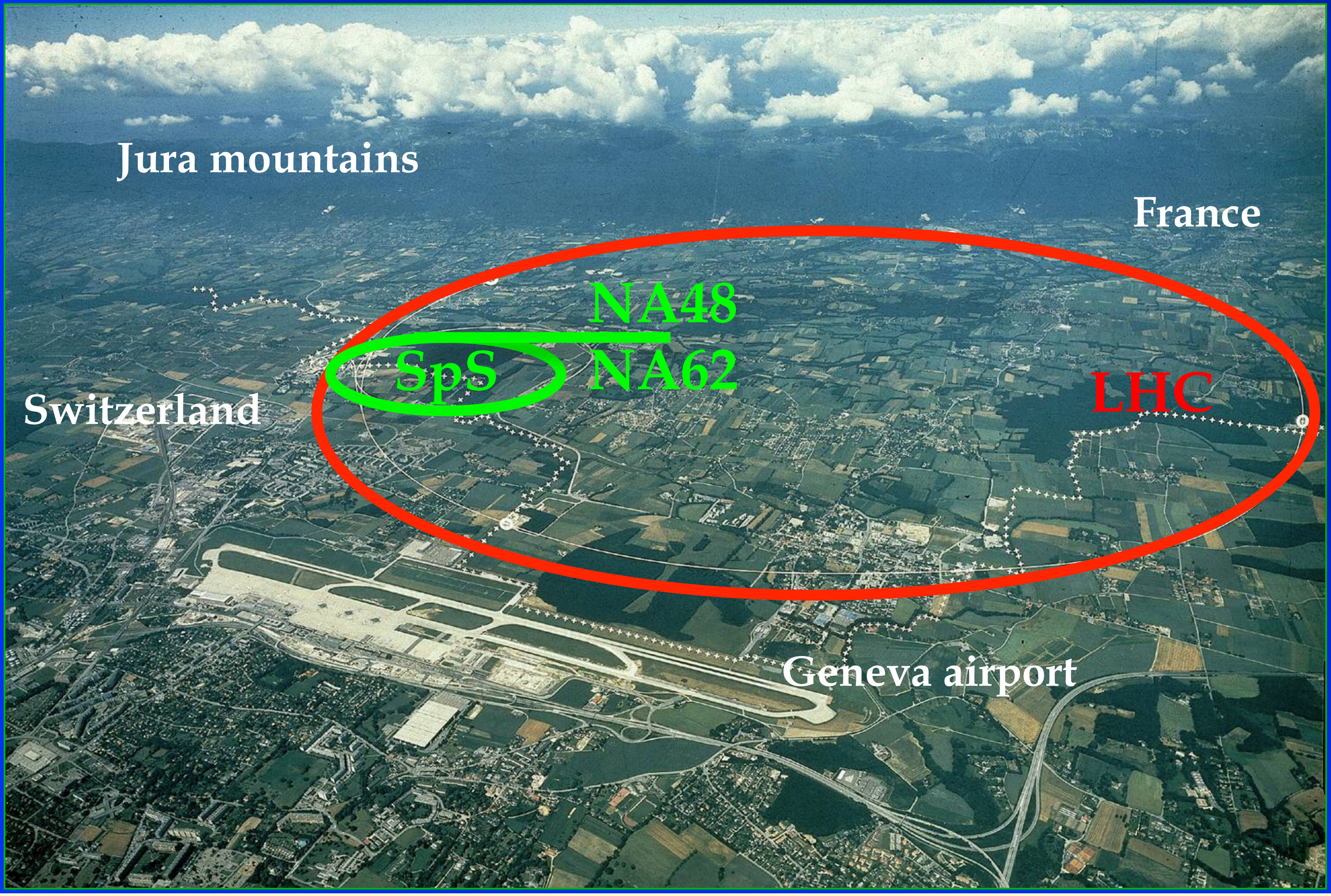
Outline

- ☑ NA48/2 and NA62 experiments
- ☑ Lepton Flavor violation in R_K
  - Physics Motivations;
  - 2009 experimental status;
  - K_{e2} and $K_{\mu 2}$ data samples;
  - Background studies & systematic effects;
  - NA62 R_K final result on 40% of the data sample;
- ☑ Lepton number violation in $K^+ \rightarrow \pi^- \mu^+ \mu^+$
- ☑ Conclusion and prospects;

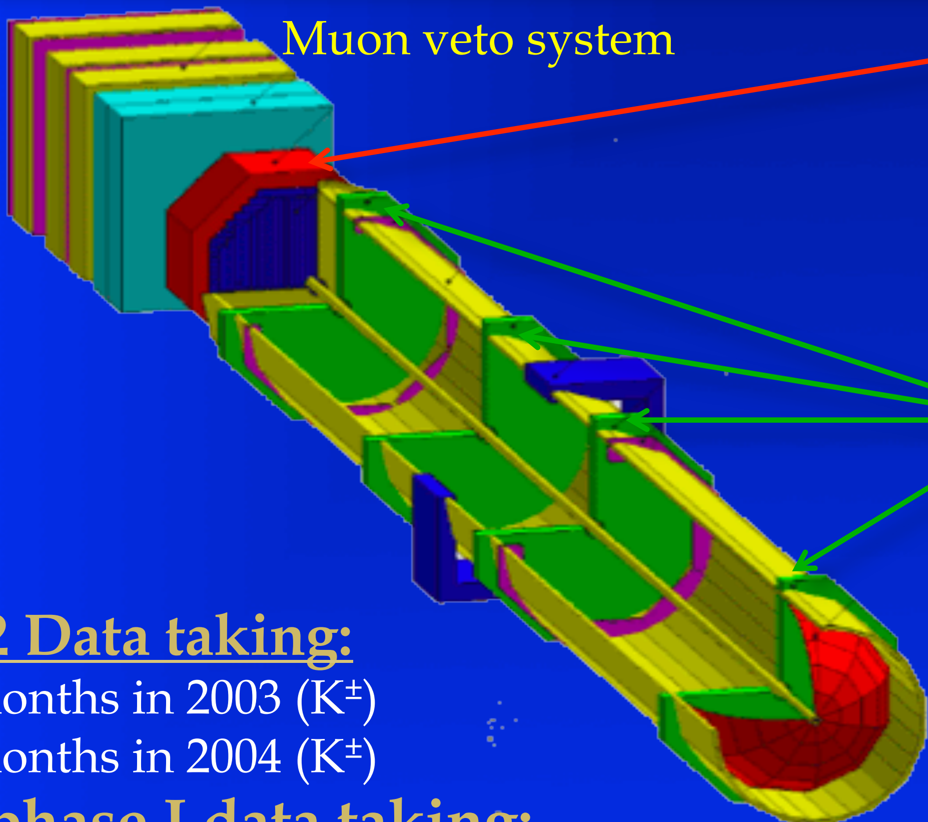
NA62 @ CERN SpS North Area



NA62 collaboration:

Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

NA48/2 and NA62 detector



LKr EM calorimeter

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\%$$

$$\sigma_{x,y} < 1.3mm$$

Spectrometer

- 4 Drift Chambers

- Magnet

$$\frac{\sigma(p)}{p} = 0.47\% \oplus 0.02 \times p(GeV)$$

$$\sigma_{VTX}^{x,y} \sim 2mm$$

Trigger Hodoscope

$$\sigma_t \approx 150ps$$

NA48/2 Data taking:

- Six months in 2003 ($K^{\pm}$)
- Six months in 2004 ($K^{\pm}$)

NA62 phase I data taking:

- Four months in 2007 (mostly K^+ only)
- Two weeks in 2008

NA62 phase II data taking:

- Three years starting from 2013? ($K^+ \rightarrow \pi^+ \nu\nu$ data)

Lepton Flavor violation in R_K: $R_K=\Gamma(K^{\pm}\to e^{\pm}\nu_e)/\Gamma(K^{\pm}\to\mu^{\pm}\nu_\mu)$

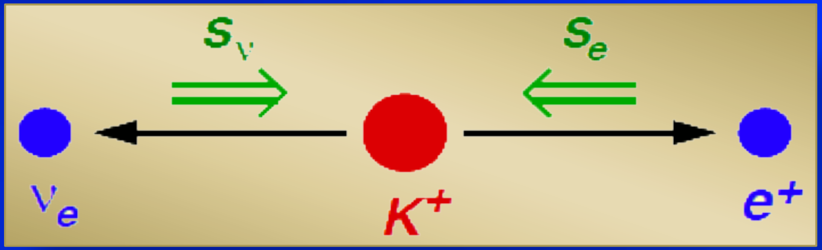
$R_K=\Gamma(K_{e2})/\Gamma(K_{\mu 2})$ in the SM

Sensitive to lepton flavor violation and its SM expectation:

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \boxed{\frac{m_e^2}{m_\mu^2}} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \boxed{\delta R_K^{rad.corr.}})$$

Few % due to: K->eν(γ) IB process

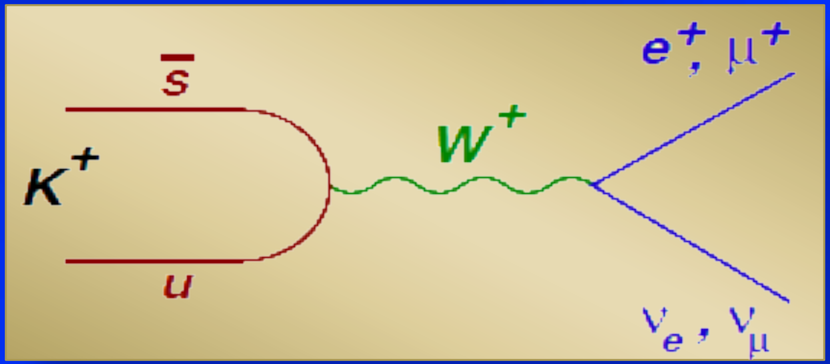
Helicty suppression factor ~10^-5



☑ SM prediction: excellent sub-permille accuracy due to cancellation of hadronic uncertainties.

☑ Measurements of R_K and R_π have long been considered as tests of lepton universality.

☑ Recently understood: helicity suppression of R_K might enhance sensitivity to non-SM



Theoretical expect. (Phys. Lett. 99 (2007) 231801):

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ (0.04% precision!)

$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

R_K beyond the SM 1 loop

2 Higgs Doublet Models – one-loop level

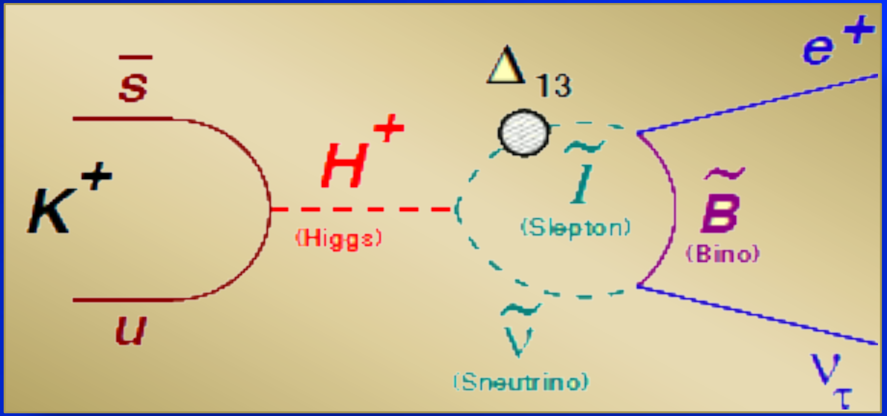
Dominant contribution to ΔR_K: $H^{\pm}$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement experimentally accessible

$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$

3 unknown parameters: $M_{H\pm}$, Δ_{13}, $\tan\beta$

PRD 74 (2006) 011701, JHEP 0811 (2008) 042



Effect in large tan β regime with a massive $H^{\pm}$ ($\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$, $M_H=500$ GeV/c^2) lead to $R_K^{MSSM} = R_K^{SM}(1+0.01)$ ~1% is measurable!

Larger effects foreseen in B decays due to $(M_B/M_K)^4 \sim 10^4$:
$B_{\mu\nu}/B_{\tau\nu}$ → ~50% enhancement;
$B_{e\nu}/B_{\tau\nu}$ → enhancement factor 10! Out of reach: $Br^{SM}(B_{e\nu}) \sim 10^{-11}$

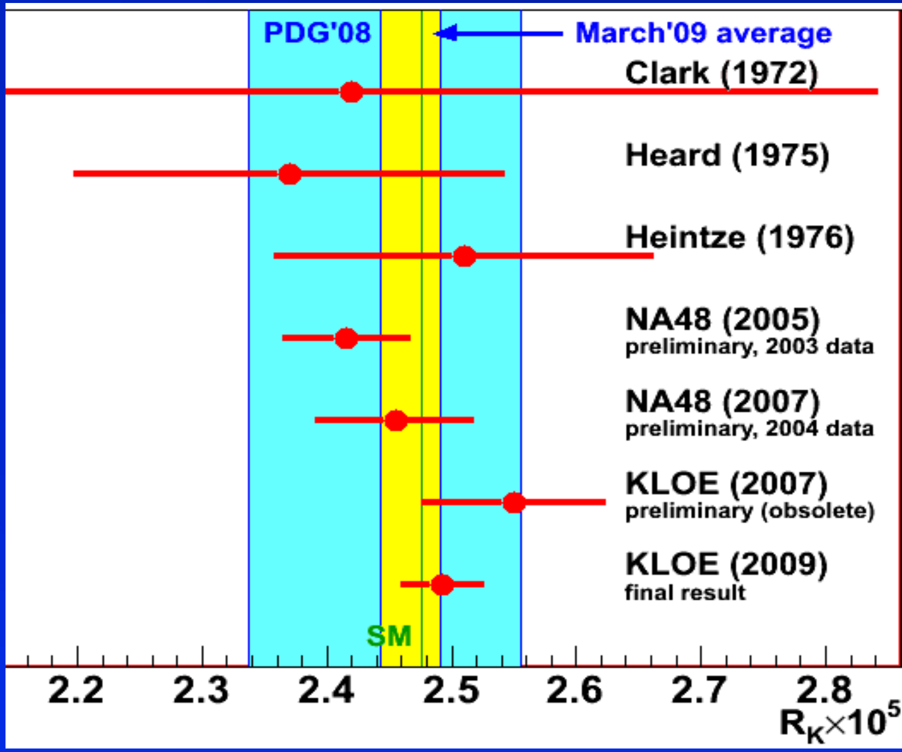
2009 R_K experimental status

After first searches in the early Seventies new interest rose by PRD 74 (2006) 01170

Studies in the NA48/2 (@ CERN) collaboration lead only to preliminary results

Recent improvement: KLOE (LNF).
Data collected in 2001–2005,
13.8K K_{e2} candidates, 16% background.
$R_K=(2.493\pm0.031)\times10^{-5}$ $(\delta R_K/R_K=1.3\%)$
(EPJ C64 (2009) 627)

R_K world average (March 2009)



NA62 (phase I) dedicated 2007 data taking goal:
~150K K_{e2} candidates, <10% background, $\delta R_K/R_K<0.5\%$:
sub % measurement able to spot for deviation from SM.

K_{e2} vs $K_{\mu 2}$ selection

Common selection criteria

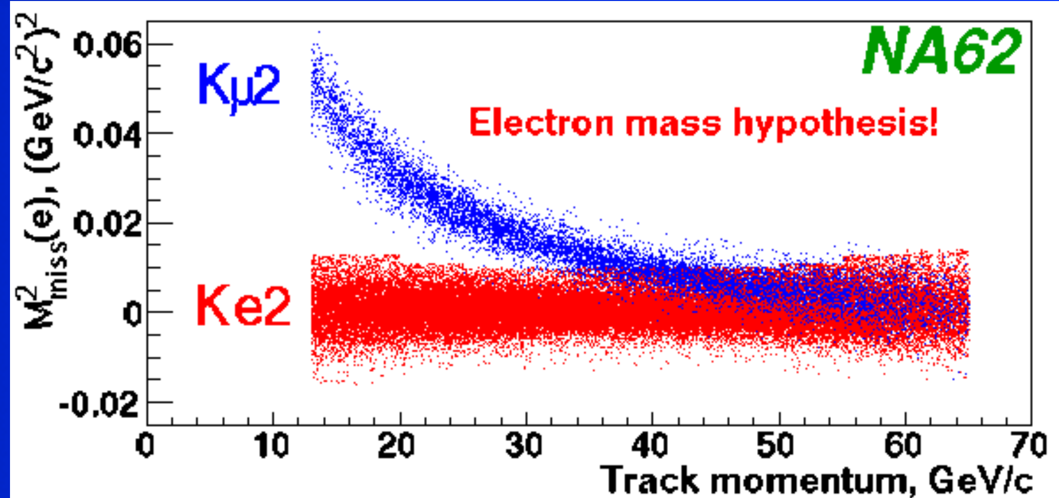
☑ One reconstructed track;
☑ Geometrical acceptance cuts;
☑ K decay vertex: closest approach of track & nominal kaon axis;
☑ Veto extra LKr energy deposition clusters;
☑ Track momentum: 13GeV/c<p<65GeV/c

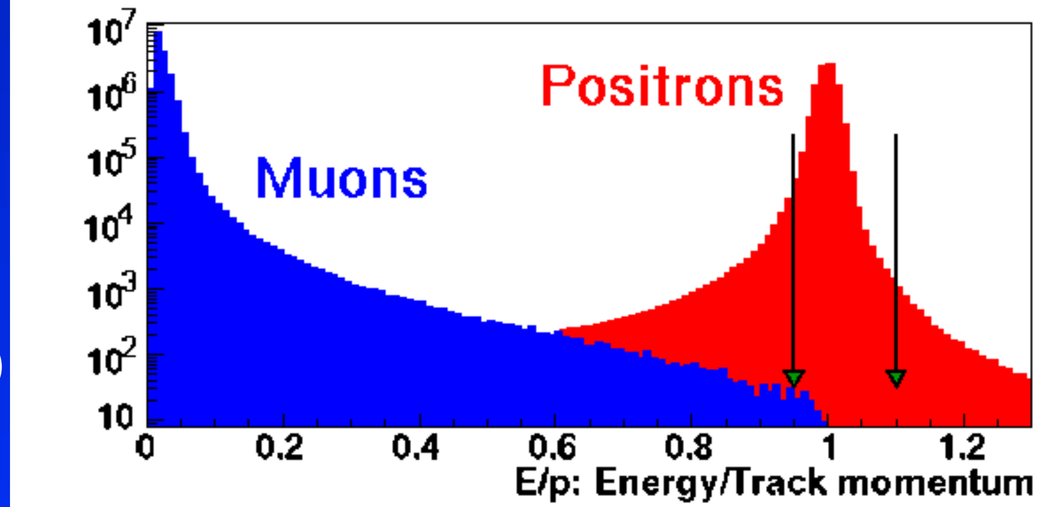
Kinematic separation $M^2_{miss}(e)$

- Missing mass $M^2_{miss}(e) = (P_K - P_l)^2$
- Good $K_{e2}/K_{\mu 2}$ separation at p_{track}<30GeV/c

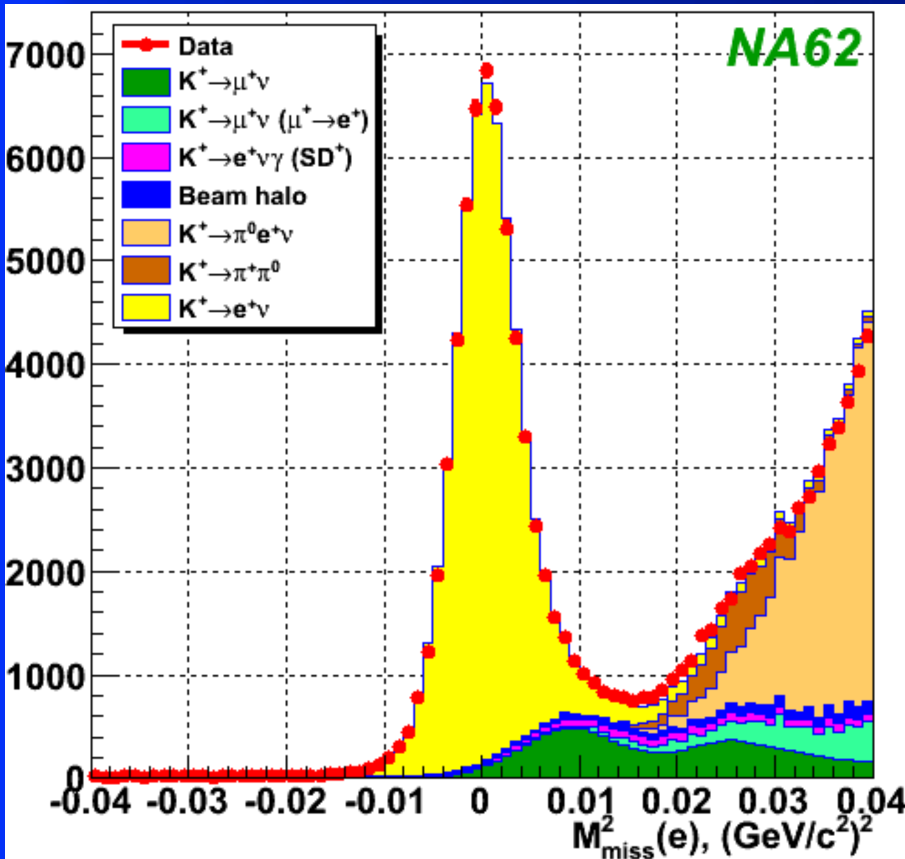
Separation by particle ID E/p

- E/p = (LKr energy dep./track momentum)
  - 0.95<E/p<1.10 for electrons,
  - E/p<0.85 for muons.
- Powerful $\mu^{\pm}$ suppression in $e^{\pm}$ sample: $f \sim 10^6$

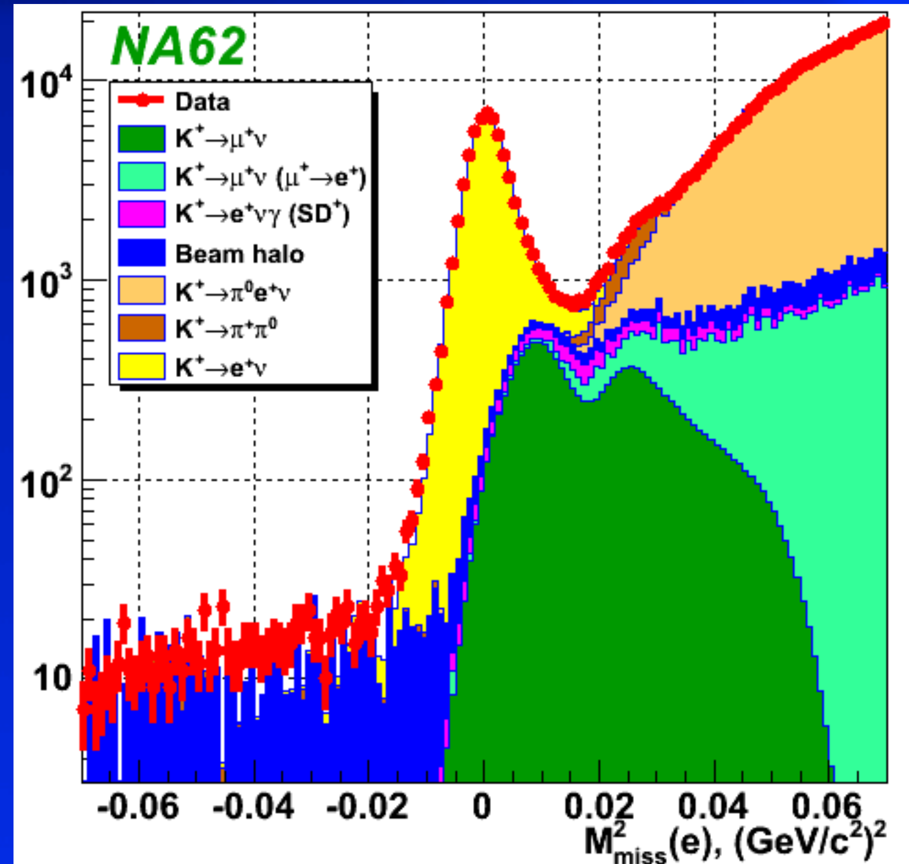




NA62 K_{e2} sample (40% data set)



NA62 result 40% data sample:
59,813 $K^+\to e^+\nu$ candidates,
(99.27±0.05) electron ID efficiency,
B/(S+B) = (8.71±0.24)%

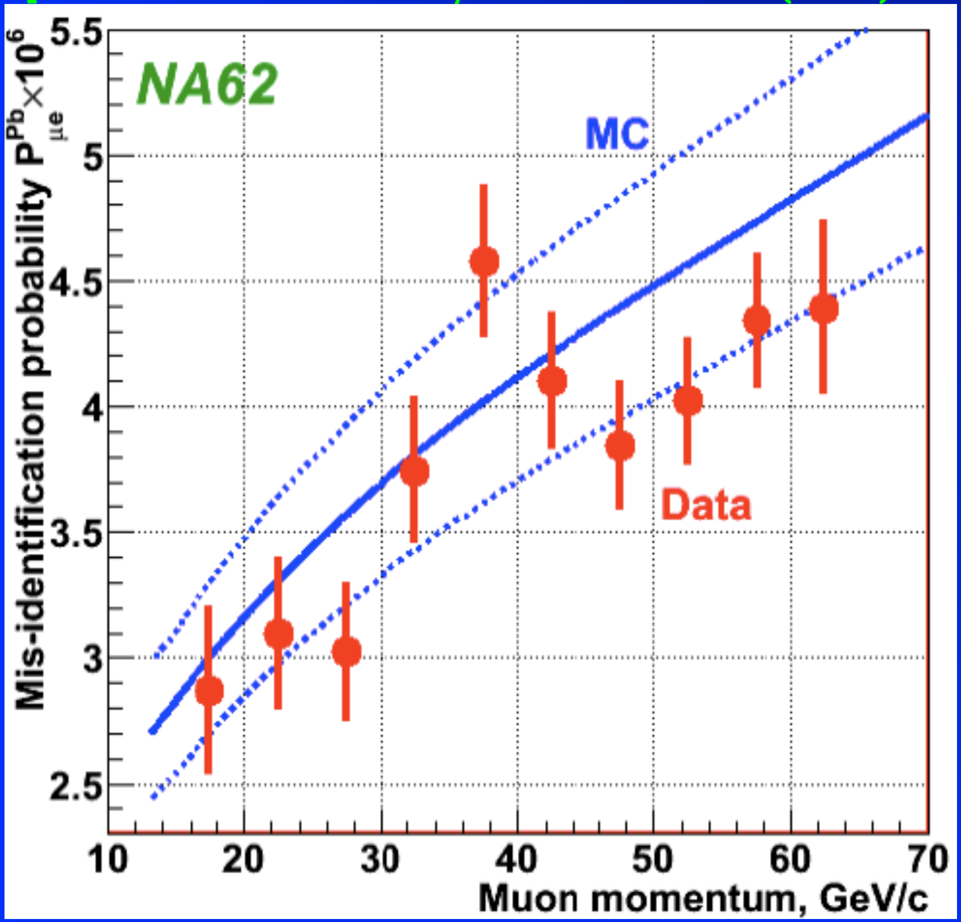


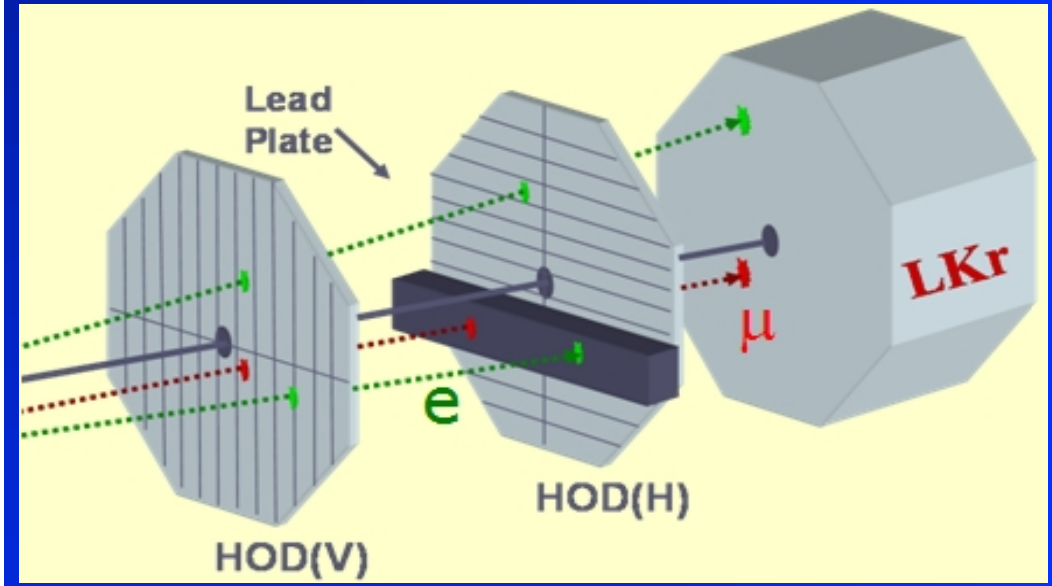
NA62 estimated total K_{e2} sample:
~123K K^+ & ~23K K^- candidates.

$K_{\mu 2}$ background measurement

P(μ→e): measurement (2007 special muon run) vs Geant4-based simulation

[Cross-section model: Phys. Atom. Nucl. 60 (1997) 576]

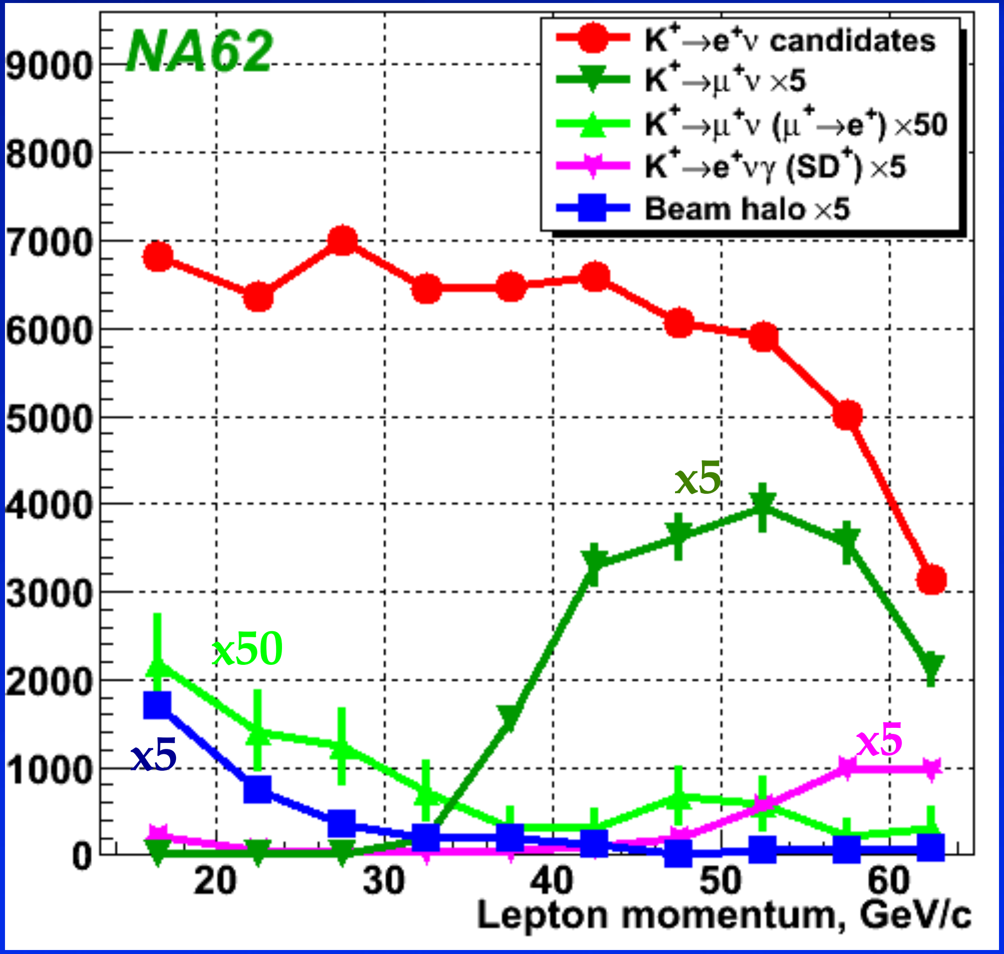




Thickness:	~$10X_0$ (Pb+Fe)
Width:	240cm (=HOD size)
Height:	18cm (=3 counters)
Area:	~20% of HOD area
Duration:	~50% of R_K runs + special muon runs

Result: B/(S+B) = (6.11±0.22)%

K_{e2} backgrounds: summary



(selection criteria, e.g. Z_{vertex} and M_{miss}^2, are optimized individually in each P_{track} bin)

Backgrounds

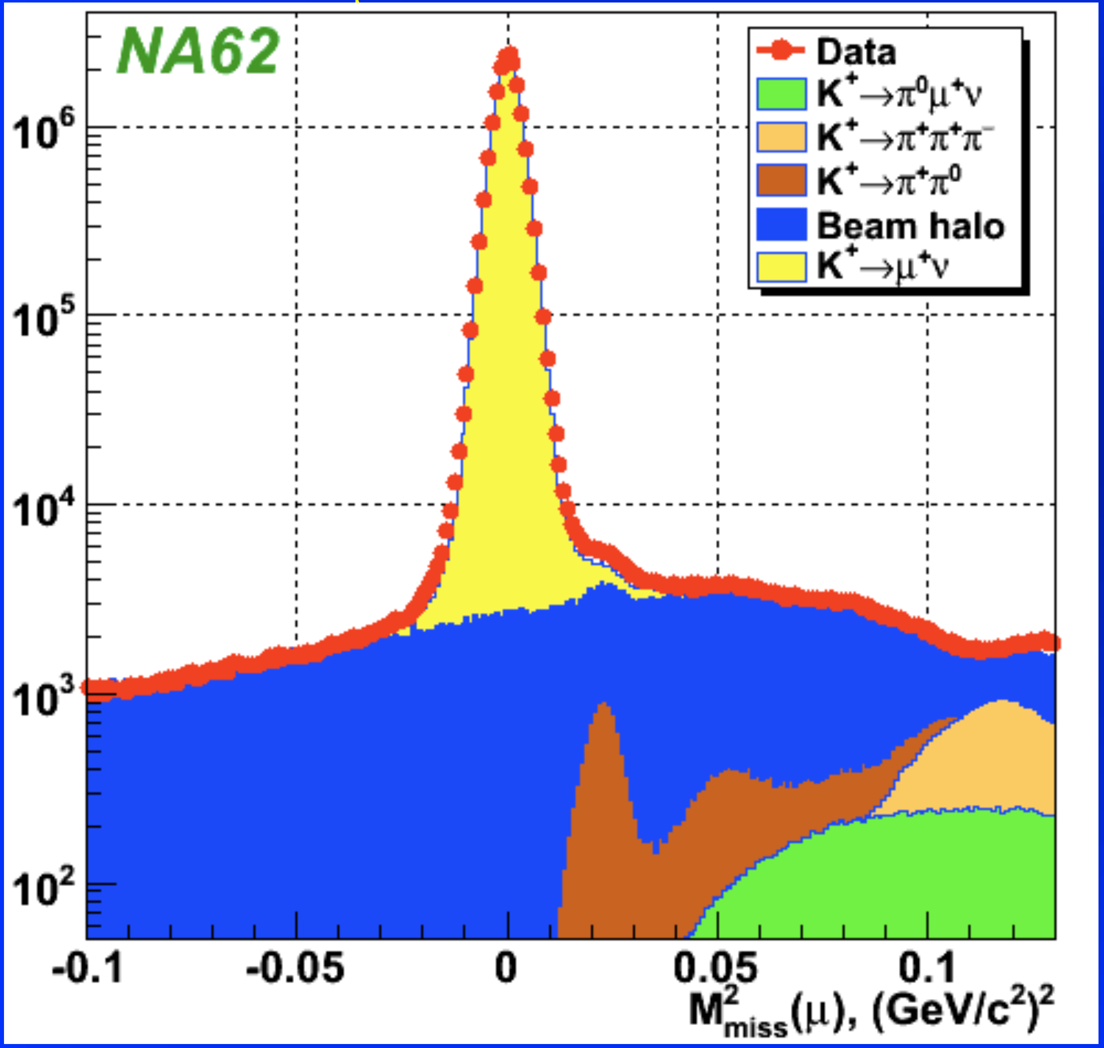
Source	B/(S+B)
$K_{\mu2}$	(6.11±0.22)%
$K_{\mu2}$ ($\mu \to e$)	(0.27±0.04)%
$K_{e2\gamma}$ (SD^+)	(1.07±0.05)%
Beam halo	(1.16±0.06)%
$K_{e3(D)}$	(0.05±0.03)%
$K_{2\pi(D)}$	(0.05±0.03)%
Total	(8.71±0.24)%

Record K_{e2} sample:
59,813 candidates
with low background
B/(S+B) = (8.7±0.24)%

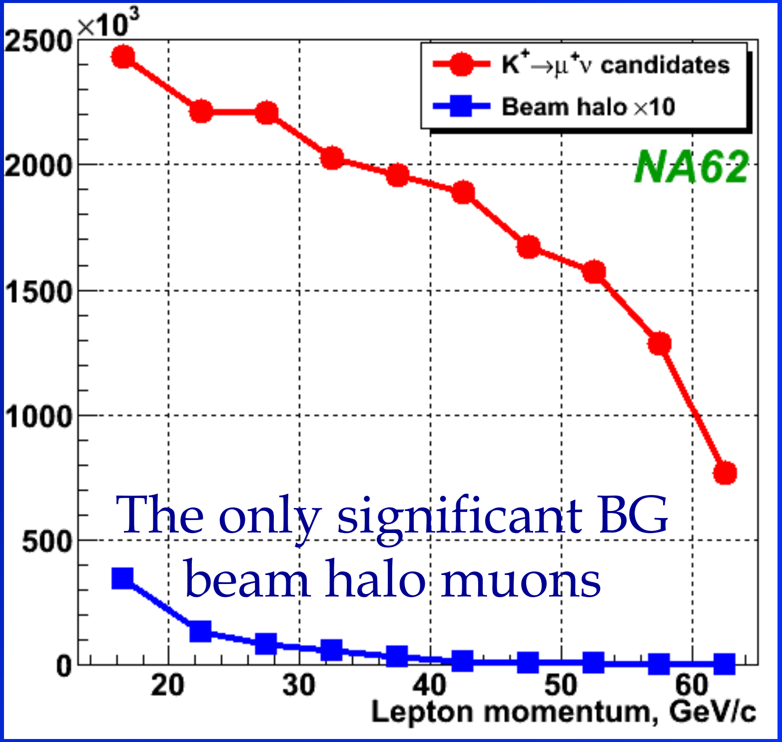
Lepton momentum bins are differently affected by backgrounds and thus the systematic uncertainties.

NA62 $K_{\mu 2}$ sample (40% data set)

$K_{\mu 2}$ candidates



Acquired using a trigger pre-scaled by D=150



18.03M candidates with a background contribution of: B/(S+B) = (0.38±0.01)%,

NA62 R_K measurement strategy

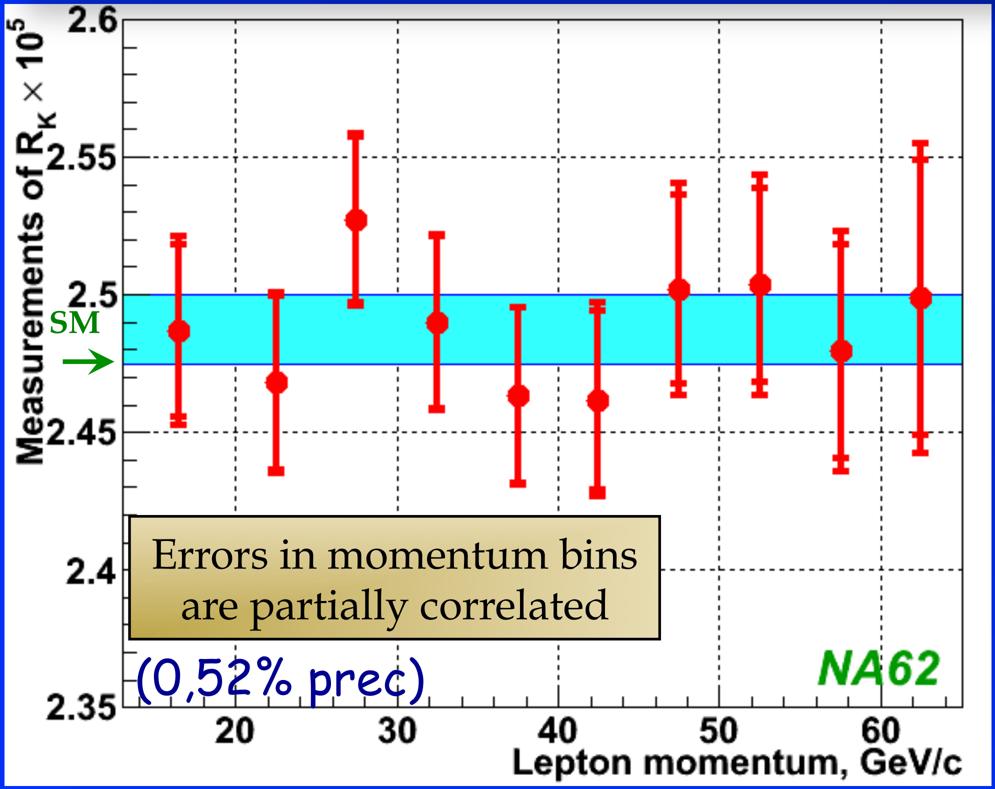
- ☑ $K_{e2}/K_{\mu2}$ candidates are collected simultaneously:
  - the result does not need any kaon flux measurement;
  - several systematic effects cancel at first order (e.g. reconstruction/trigger efficiencies, time-dependent effects).
- ☑ Counting experiment, independently in 10 lepton momentum bins
  - owing to strong momentum dependence of backgrounds
- ☑ MC simulations used to a limited extent only:
  - Geometrical acceptance and simulation of "catastrophic" bremsstrahlung by μ.

$$R_K = \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{A(K_{\mu2})\varepsilon(K_{\mu2})f_\mu}{A(K_{e2})\varepsilon(K_{e2})f_e} \cdot \frac{1}{f_{LKr}}$$

$N(K_{e2})$, $N(K_{\mu2})$	:	numbers of selected K_{l2} candidates;
$N_B(K_{e2})$, $N_B(K_{\mu2})$	:	numbers of background events in Kl2 samples;
$A(K_{e2})$, $A(K_{\mu2})$	:	MC geometrical acceptances (no ID);
f_e, f_μ	:	directly measured particle ID efficiencies;
$\varepsilon(K_{e2})/\varepsilon(K_{\mu2})$	:	E_{LKr} EM calorimeter trigger condition efficiency;
$f_{LKr}=0.9980(3)$	:	global LKr EM calorimeter readout efficiency.

NA62 R_K final result (40% data set)

$R_K = (2.487 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5}$
$R_K = (2.487 \pm 0.013) \times 10^{-5}$ PLB 698 (2011) 105–114

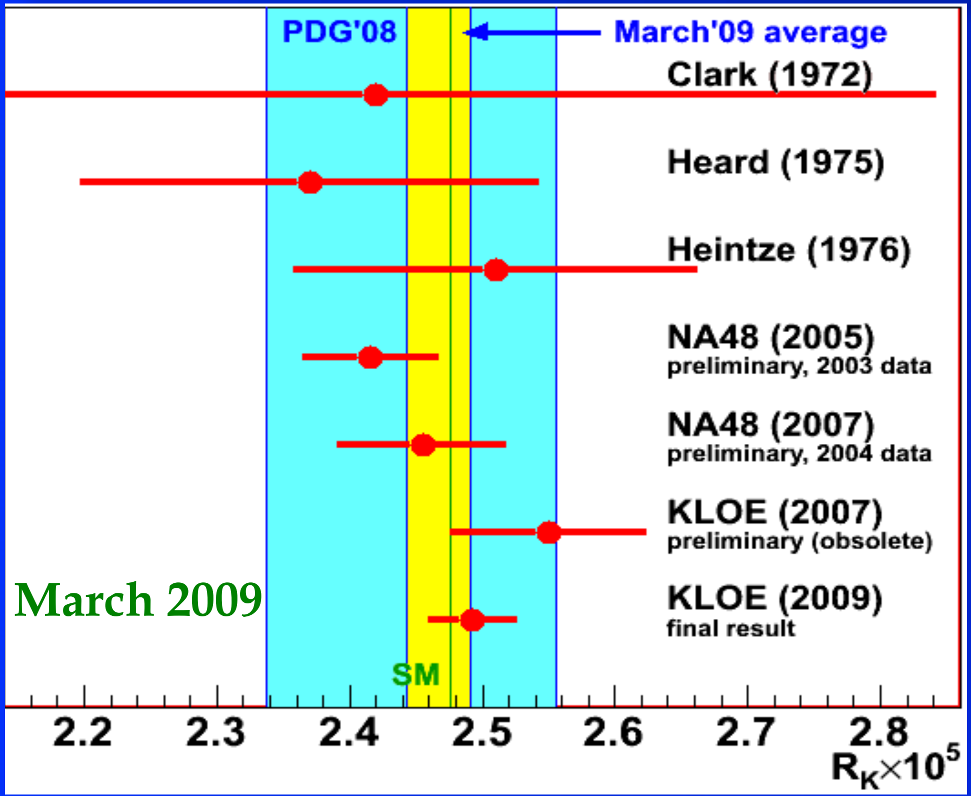


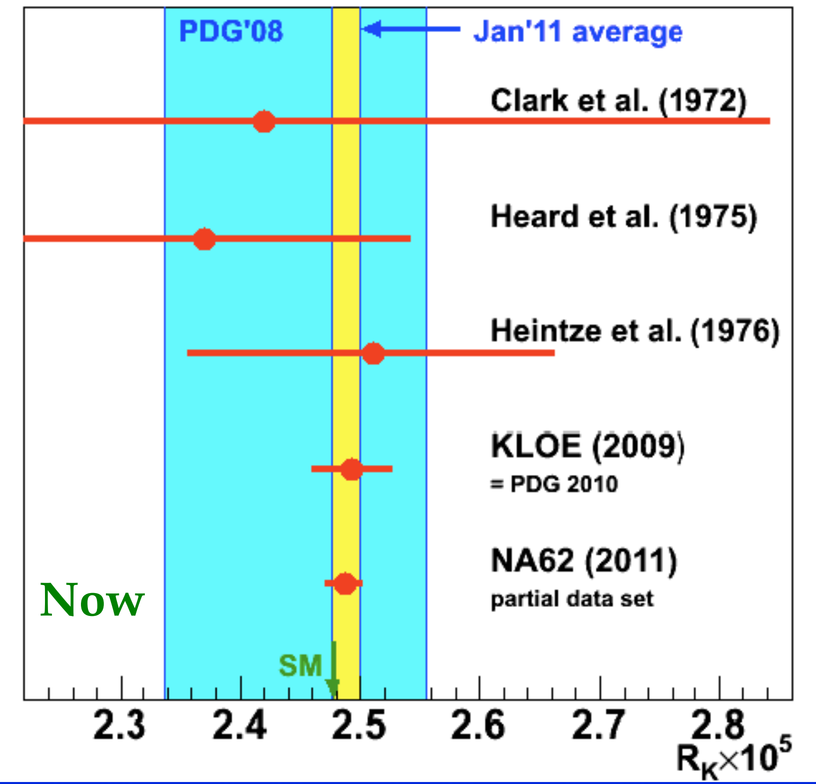
Uncertainties

Source	$\delta R_K \times 10^5$
Statistical (0.44%)	0.011
$K_{\mu 2}$(BG)	0.005
Beam halo (BG)	0.001
$K_{e2\gamma}$ (SD^+) (BG)	0.001
K_{2p} Ke3	0.001
Spectrometer align	0.001
Helium purity	0.003
Acceptance (MC)	0.002
Positron ID	0.001
1TRK trigger eff.	0.002
Lkr readout eff	0.001
Total (0.52%)	0.013

The whole 2007 sample will allow statistical uncertainty ~0.3%, total uncertainty of ~0.4%.

NA62 R_K: effect on world average





NA48/2 preliminary results excluded they are superseded by NA62 one. KLOE preliminary result excluded superseded by KLOE final.

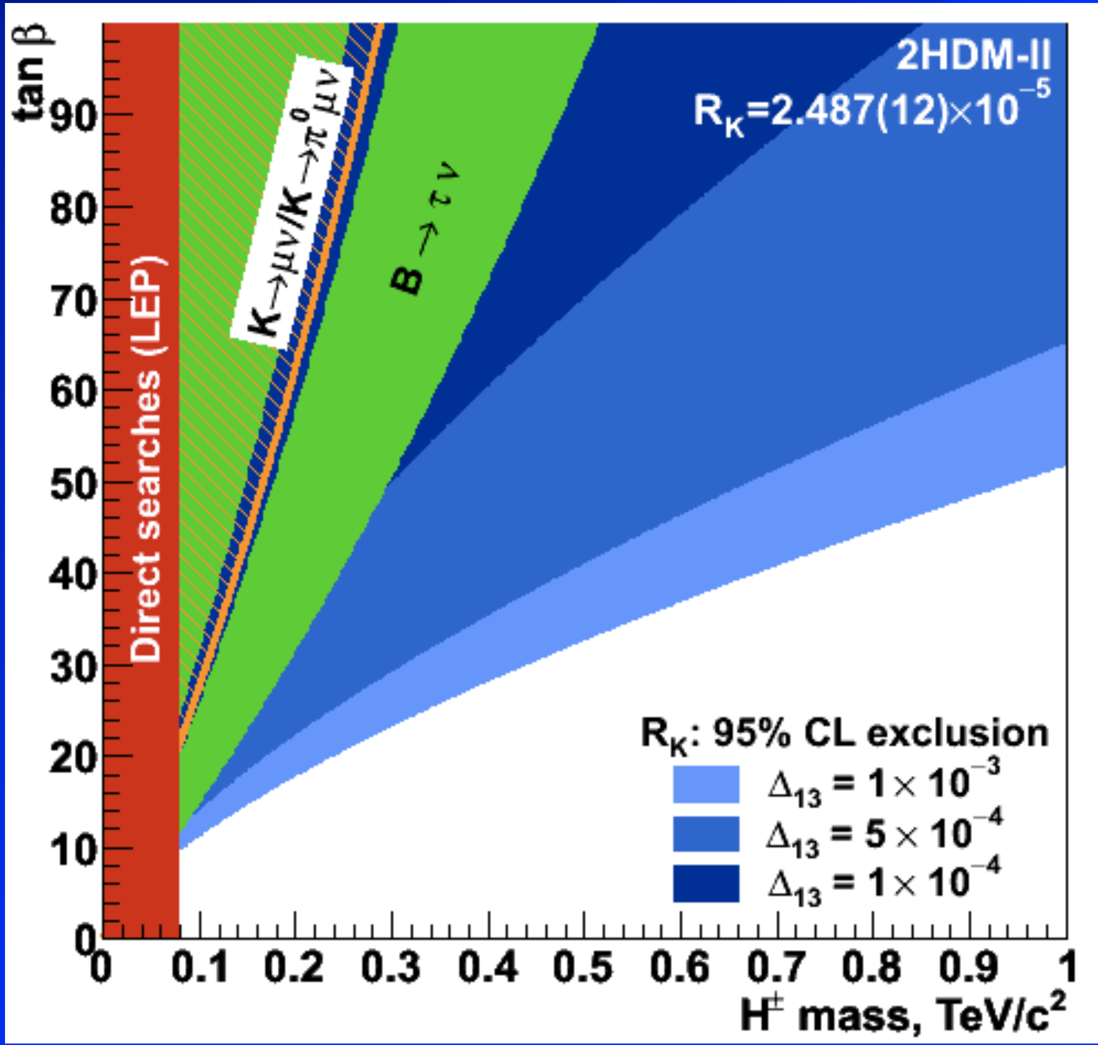
World average	$\delta R_K \times 10^5$	Precision
March 2009	2.467±0.024	1.%
Jaunuary 2011	2.487±0.012	0.5%
Theory	2.477±0.001	0.04%

R_K: sensitivity to new physics

R_K world average is currently in agreement with the SM expectation at ~0.8 σ.

Any significant enhancement with respect to the SM value would be an evidence of new physics.

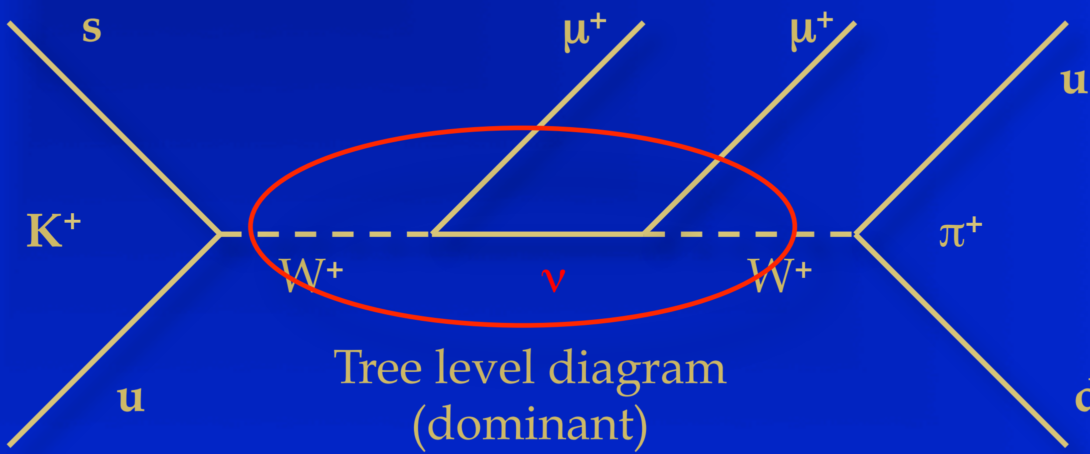
This result can be used to exclude the presence of $H^\pm$ in a wide range of $M_{H\pm}$



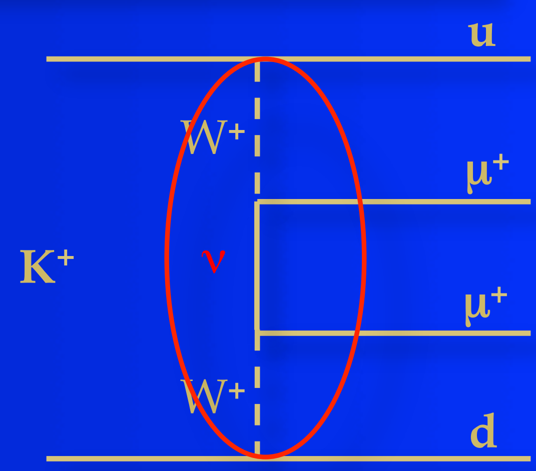
Even for tiny values of the LFV slepton mixing Δ_{13}, sensitivity to $H^\pm$ in $R_K = K_{e2}/K_{\mu 2}$ is better than in $B \to \tau\nu$

Lepton number violation in $K^+ \rightarrow \pi^- \mu^+ \mu^+$

Lepton number violation in $K^+ \rightarrow \pi^- \mu^+ \mu^+$



Tree level diagram
(dominant)

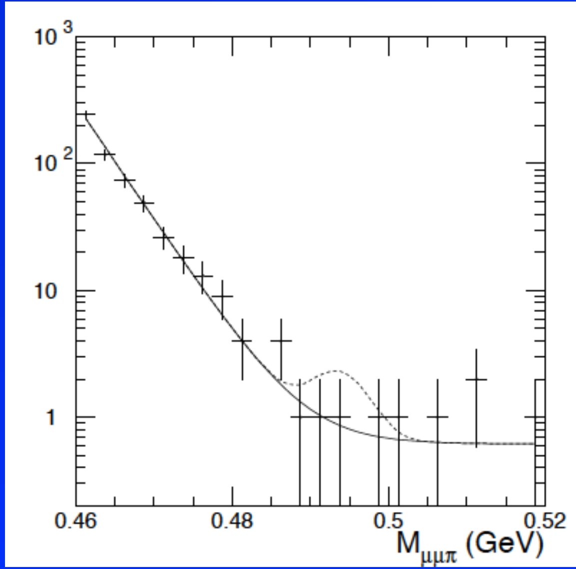


$K^+ \rightarrow \pi^- \mu^+ \mu^+$ proceeds if the neutrino ν is a Majorana particle:

$$BR \approx 10^{-8} \times (\langle m_{\mu\mu} \rangle / \mathrm{TeV})^2$$

$\langle m_{\mu\mu} \rangle$ being the effective Majorana neutrino mass

K. Zuber, PLB 479 (2000) 33;
L. Littenberg, R. Shrock, PRB491 (2000) 285



The best experimental limit to these processes has been set by E865 using a sample of 400 $K^+ \rightarrow \pi^+ \mu^- \mu^+$. From the study of the background events they found:

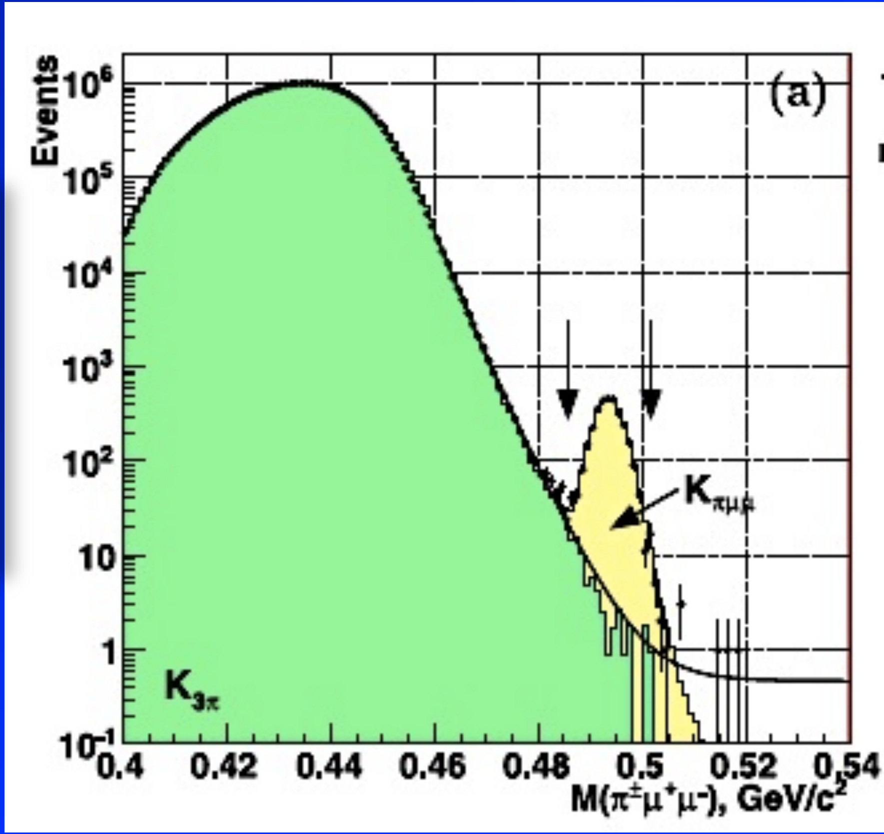
$BR(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 3 \times 10^{-9}$ 90% CL

Phys.Rev.Lett 85:2877-2880,2000

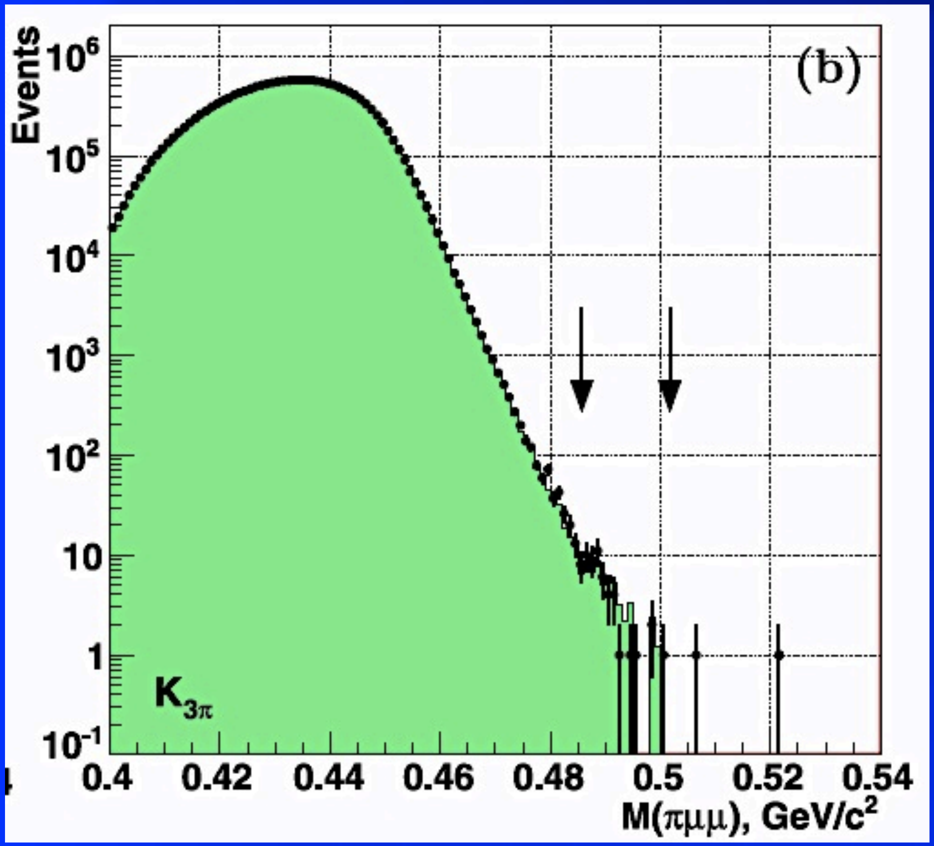
NA48/2 $K^\pm \to \pi^\pm \mu^+ \mu^-$ sample

- ☑ 3,120 candidates (~4 times world sample) PLB 697 (2011) 107
- ☑ (3.3±0.7)% background
- ☑ Branching fraction, CPV and Forward Backward asymmetries measured

Exp	Beam	Evt	BRx10^8
E787	K^+	207	5.0±0.4±0.6±0.7
E865	K^+	430	9.22±0.60±0.49
HyperCP	$K^\pm$	110	9.8±1.0±0.5
NA48/2	$K^\pm$	3120	9.62±0.21±0.11±0.07



Search for LNV $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$



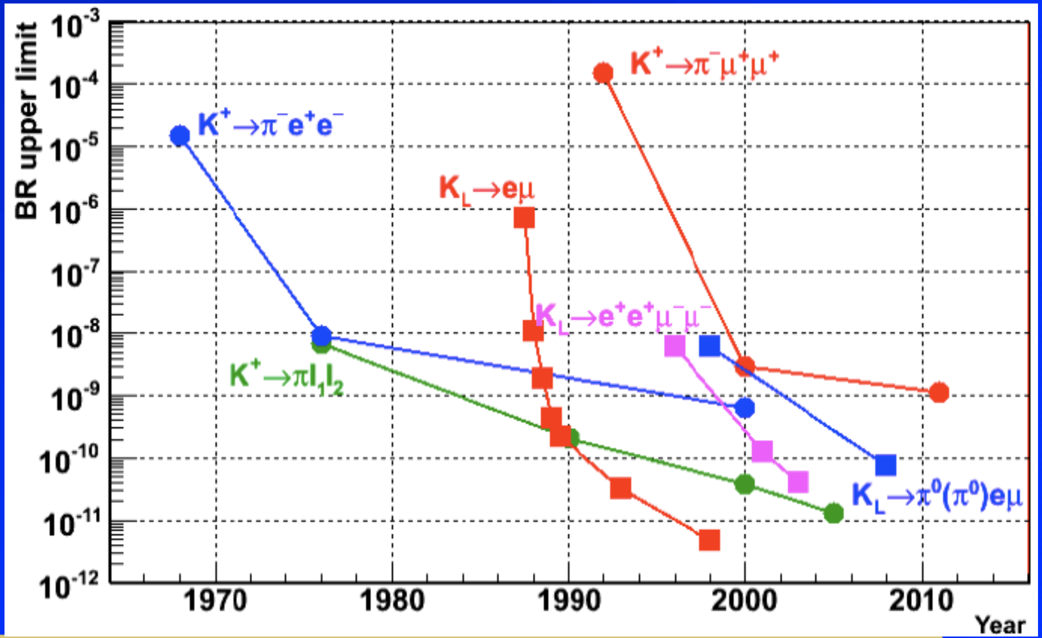
Candidate Lepton Number Violating $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$:

$N_{data} = 52$ PLB 697 (2011) 107

$N_{bkg} = 52.6\pm19.8_{syst}$ (MC predicted)

$BR(K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1\times10^{-9}$ (90% CL)

allowing a bound on the effective Majorana neutrino mass $<m_{\mu\mu}> <$ of 300 GeV/c^2 to be established



A factor of 3 improvement on the upper limit for $BR(K^+\to\pi^-\mu^+\mu^+)$ wrt E865 (2000)

Conclusion

☑ Due to the helicity suppression factor (~10^5) of the K_{e2} decay, the ratio R_K is stringent test of the Standard Model.

☑ NA62 during data taking in 2007/08 has collected K_{e2} sample ~10 times the world sample with a low 8.7% background.

☑ Final NA62 result based on ~40% of the NA62 K_{e2} candidates leads to: $R_K = (2.487 \pm 0.013) \times 10^{-5}$, reaching ~ 0.5% accuracy

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☑ The R_K value is compatible to the SM prediction in within 0.8σ

☑ The precision is expected to be improved to better than $\delta R_K/R_K = 0.4\%$ using the full NA62 (Phase I) data sample and pushed to 0.2% NA62 (Phase II).

☑ R_K measurement with ~0.2% precision is expected to be performed in the framework of the NA62 (phase II) experiment.

☑ The best upper limit on LNV in $BR(K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1 \times 10^{-9}$ 90%CL has been set

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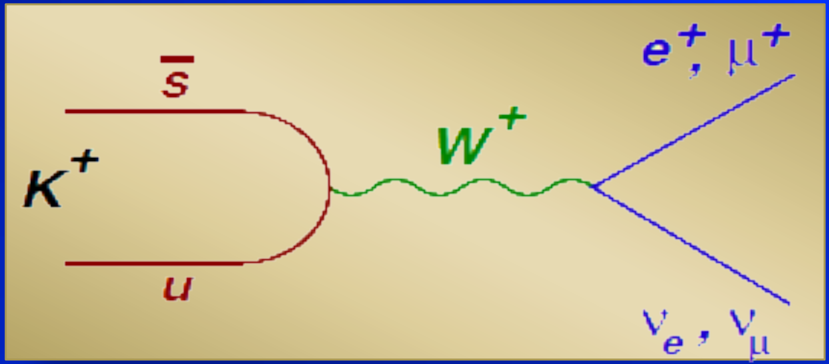
Backup slides

Leptonic meson decays: $P^+ \to l^+ \nu$



2 Higgs Doublet Models – tree level

Suppressed by elicity (mostly in Ke2)

Lepton Flavor Universality only phase space correction needed in the leptonic vertex

QED corrections needed to treat the electron radiation

2 Higgs Doublet Models – tree level

K_{l2} can proceed via exchange of charged Higgs H^+ instead of W^+

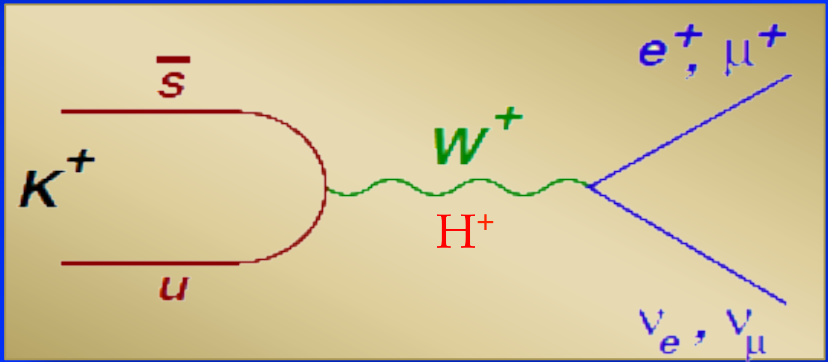
Using $M_{H+}=500\text{GeV}/c^2$, $\tan\beta=40$

$\pi^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \approx -2\times10^{-4}$

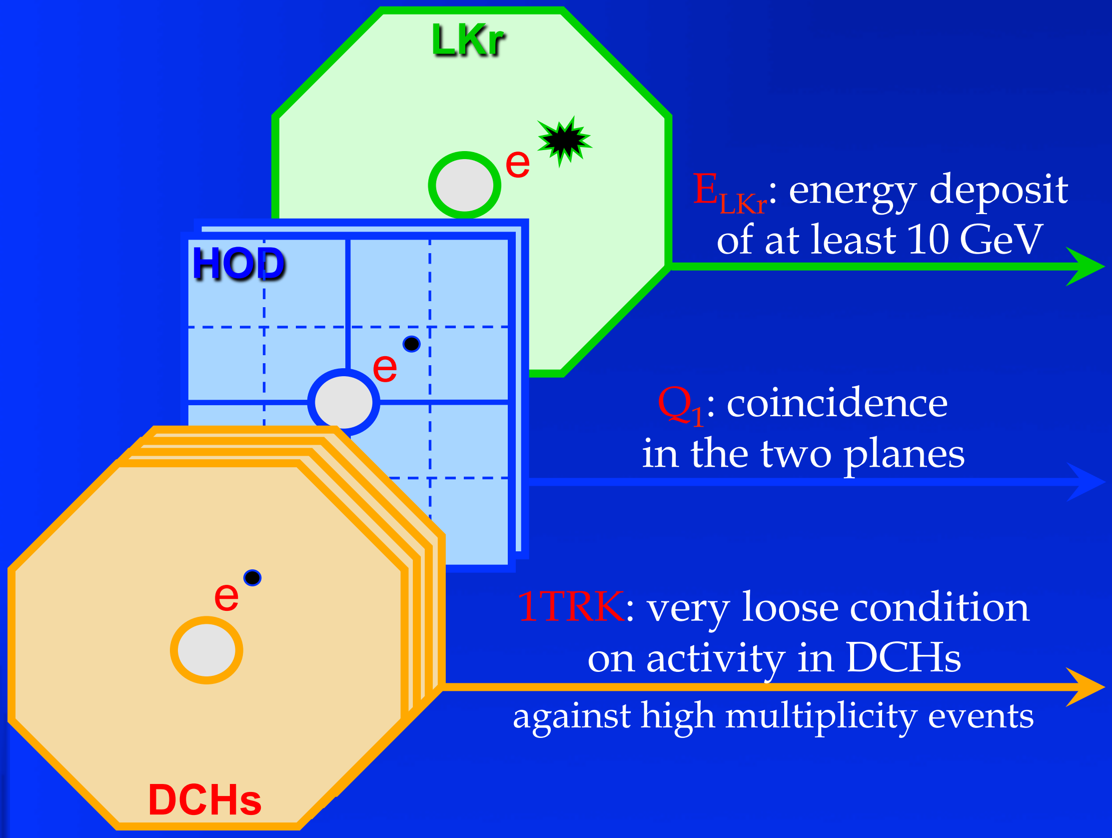
$K^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_K/m_H)^2 \tan^2\beta \approx -0.3\%$

$D^+_s \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_D/m_H)^2\, (m_s/m_c) \tan^2\beta \approx -0.4\%$

$B^+ \to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_B/m_H)2 \tan^2\beta \approx -30\%$



Trigger logic



Minimum bias (high efficiency, but low purity) trigger configuration used

K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$. Purity ~$10^{-5}$.

$K_{\mu 2}$ condition: $Q_1 \times 1TRK/D$, downscaling (D) 50 to 150. Purity ~2%.

- Efficiency of K_{e2} trigger: monitored with $K_{\mu 2}$ & other control triggers.
- E_{LKr} inefficiency for electrons measured to be (0.05±0.01)% for p_{track}>15 GeV/c.
- Different trigger conditions for signal and normalization!

Beam halo background

Electrons produced by beam halo muons via $\mu \rightarrow e$ decay can mimic K_{e2} decays

<u>Halo background measurement:</u>

☑ Halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%).

☑ ~90% of the data sample is K^+ only, ~10% is K^- only.

☑ K^- sample is used to directly measure K^+ halo component and vice versa

- K^+ selection applied to K^- run to calculate halo BG probability

The background is measured to sub-permille precision, and strongly depends on decay vertex position and track momentum.

The selection criteria (esp. Z_{vertex}) are optimized to minimize the halo background.

$B/(S+B) = (1.16 \pm 0.06)\%$

Uncertainty is due to the limited size of the K^- control sample.